Experimental Methods for Science and Engineering Students

Responding to the developments of the past 20 years, Les Kirkup has thoroughly revised his popular book on experimental methods, while retaining the extensive coverage and practical advice from the first edition. Many topics from that edition remain, including documenting experiments, dealing with measurement uncertainties, understanding the statistical basis of data analysis and reporting the results of experiments. This new edition reflects the burgeoning impact of digital technologies on the way experiments are performed, analysed and presented, and the increased emphasis on the importance of communication skills in reporting the results of experiments. The book is ideally suited to science and engineering students, particularly those new to laboratory or field-based work, who require a coherent and student-friendly introduction to experimental methods. Exercises, worked examples and end-of-chapter problems are provided throughout the book to reinforce fundamental principles.

Les Kirkup is an Adjunct Professor in the Faculty of Science at the University of Technology, Sydney, and Honorary Professor in the School of Physics at the University of Sydney. He has devised laboratory programmes and taught extensively in undergraduate laboratories. He has been recognised for his work in supporting student learning in laboratories with two national fellowships and the Australian Institute of Physics Education Medal.

"The first edition of Les Kirkup's classic was for years the only set book for our first-year engineering students. This new edition reflects the rapid progress in digital instrumentation, data processing and communications since then. Even for a generation used to the minimalist style of online help, Kirkup's style makes it an easy read as well as an essential reference for error assessment. Its greatest strength lies in helping the reader to foresee experimental options which avoid the pitfalls of experimental error *before* they require correction. With so many examples, drawn from so many fields, every STEM subject student needs this book!"

– Pat Leevers, *Imperial College London*

"*Experimental Methods for Science and Engineering Students* is the ideal textbook to give students a solid foundation in the difficult tasks of designing, conducting and interpreting the results of experiments. I have used it as the textbook on my undergraduate course in Experimental Methods for several years. The students found it to be an excellent resource filled with useful and approachable examples. The updated edition has expanded to aid students in report writing and making presentations about their results. The new edition also introduces modern hardware used for data acquisition and covers data analysis in common software packages. This book is a comprehensive guide helping students develop all the skills necessary to become a competent experimentalist."

– Dr. John Kennedy, *Trinity College Dublin*

"Having used and appreciated the first edition of Les Kirkup's book, it's great to see this update. It covers the whole process of experimental work. Highlights are how the book explains the fundamentals of `how it works' in relation to: the role of technology in modern experimentation, dealing with uncertainties in data, and a range of science communication formats that are commonly used by students and professionals in science and engineering. Techniques are helpfully illustrated with worked examples, using data from experiments that are relevant to the target students. Exercises, with answers, provide a valuable resource for practice. Les Kirkup has a clear writing style, and his extensive experience in teaching laboratory science shows in the advice that he provides about situations where students often feel confused about what to do. This book encourages students to think about their experiments, in a way that enables them to improve their outcomes."

– Margaret Wegener, *The University of Queensland*

Experimental Methods for Science and Engineering Students

An Introduction to the Analysis and Presentation of Data

SECOND EDITION

Les Kirkup

University of Technology, Sydney

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To Janet

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Preface to the Second Edition

I'd like to thank Simon Capelin and Cambridge University Press for the opportunity to update this book. I also thank all those who commented on the first edition and encouraged me to review and revise the text.

My goals in revising the text were to build on the methods appearing in the first edition that remain the backbone of experimental work, while including other topics that have assumed greater prominence because of, for example, changing emphases within science and engineering courses. I have taken the opportunity to include recent references and suggestions for further reading, where these expand consideration of the topics in this book. There is an emphasis on examples and exercises that reinforce principles, as those principles are introduced.

Like its predecessor, this edition seeks to assist students in their experimental work, especially students in their early years of study in a college or university course in science or engineering who are required to engage in laboratory (or field-based) work. That work might include (a) carrying out experiments where the aims of the experiments and the methods are prescribed, or (b) open-ended experiments, which give students the scope and responsibility to decide what they will do and how they will do it. As with the first edition, several topics in the book, such as reporting findings of experiments, should be of relevance to those who carry out experiments up to senior stages of an undergraduate course.

The new edition recognises technological advances that have occurred since the first edition was published with respect to carrying out experiments, and the increased emphasis on reporting findings using various modes of communication. I have indicated where useful information relating to experimental methods can be found on the Internet. I recognise that for all its virtues, the Internet can be frustrating when material is moved or removed. I apologise if or when any links I have included become 'broken'.

The chapter on the pocket calculator in the first edition has been removed, as the type of calculator featured is no longer available. With the enormous range of calculator options available to students, including calculator apps for smartphones, it is difficult to write a chapter on calculator use that would be of benefit to a large fraction of readers.

The students I have worked with have stimulated me to think carefully about the resources, examples and advice that will be useful to them as they plan, carry out and report experiments. More broadly, I hope the book will encourage a heightened awareness of the power, utility and transferability of the abilities students acquire

through doing experimental work. Such abilities are of enduring value, irrespective of a student's career destination.

I have enjoyed writing this book enormously. I have sought to harness what I have learned from my students, colleagues, the writings of other authors and my own experiences of laboratory work to create a resource sympathetic to the needs of science and engineering students.

I would like to acknowledge those who have influenced this edition, offered encouragement and suggestions for inclusion or provided ideas for exercises and problems:

Mike Cortie, Yvonne Davilla, Angus Gentle, Neela Griffiths, Shirin-Rose King, Andrea Leigh, Juliette Massicot, Blair Nield, Lauren O'Brien, Anoj Poudyal, Greg Skilbeck (University of Technology Sydney)
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I would also like to thank David Raul, Jennifer Soriano and Shital Hamal for the convivial environment in which I completed much of this book.

Les Kirkup

Preface to the First Edition

As an organiser and demonstrator in undergraduate laboratories, I have never been entirely satisfied with the ad hoc arrangements made to assist those new to experimentation so that they may come to grips with vital topics such as uncertainties, graphing and keeping a laboratory notebook. It was this dissatisfaction, coupled with a belief that other topics such as report writing and the use of computers in the gathering, presentation and analysis of experimental data should be given more emphasis in texts concerned with experimental methods, that encouraged me to put pen to paper.

Experimental work should be amongst the most stimulating and satisfying activities in any course of study in science or engineering. A well-designed and executed experiment followed by *proper data analysis* offers insights into a process or phenomenon which are unlikely to be provided by a theoretical study alone. It is what goes into the *proper analysis* of experimental data which dominates the subject matter of this book. I have tried to describe the tools and techniques that will assist those engaged in presenting and analysing experimental data as part of their undergraduate studies in science or engineering.

This book is aimed at those beginning an undergraduate course of study in the physical sciences or engineering who have a significant laboratory component to their subjects. Early chapters assume very little prior knowledge of the techniques of data analysis. However, several topics in the book go beyond first-year level, and many of the matters raised should be of relevance to those engaged in experimental work up to senior stages of an undergraduate course.

With regard to the formulae that appear in the text, I have preferred to emphasise the background and assumptions relevant to a particular formula rather than to deal in depth with the mathematics of its derivation. Wherever possible, discussion of a formula is followed up with an appropriate 'worked' example. I have given references in the text to where greater details concerning formula derivation can be found.

The book divides into three sections:

(i) Chapters 1 to 4 cover the basic groundwork appropriate to first-year studies in science and engineering in the areas of notebook keeping, characterising experimental data, graphing and uncertainties.

(ii) Chapters 5 to 7 discuss the statistical analysis of experimental data and the important topic of least-squares fitting of functions to data as well as addressing the crucial area of communicating the findings of an experiment in the

form of a report. Though 'long' reports are generally given more emphasis beyond first year, I feel that it is a topic of such importance that it deserves fuller treatment than a brief mention of the headings found in a report. The material contained in these chapters is likely to be most useful to data analysis problems beyond first-year undergraduate level.

(iii) Chapters 8 and 9 deal with the application of technology to the analysis and presentation of data. Though pocket calculators have been widely available for over 20 years, their usefulness for analysing experimental data is rarely dealt with explicitly in a book of this type. Superseding the calculator in power is the microcomputer, and the availability of excellent hardware and software for presentation and analysis purposes has encouraged me to write about these matters.

Because of the diverse range of topics that appear in this book I have included, in an appendix, details of other books which can be referred to for more information. As microcomputers are now commonly found in undergraduate laboratories assisting with data gathering as well as analysis, the last appendix offers an introduction to this topic.

I have gained enormous enjoyment from writing this book (and learned a few things along the way!) and look forward to any feedback it may provoke. Suggestions from students have been mostly heeded (more examples, more examples!) and I hope this has made for a book in keeping with their needs.

There are many people who have helped make this book possible. In particular I would like to thank my publishing editor, Derelie Evely, for her enthusiastic support of the project and her deadlines. Equal thanks are owed to my university for granting me the time away from my normal duties to complete the book, and to Professor David Rawson of the University of Luton, England for providing a congenial environment in which to carry out some of the work. I'd also like to thank the following reviewers and providers of ideas for examples, experimental data and problems:

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Les Kirkup